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ANALYTICAL CHEMISTRY HANDBOOK

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SECTION 13
MASS SPECTROMETRY

Mass spectrometry is the analytical technique that provides the most structural information for the least amount of analyte material. It provides qualitative and quantitative information about the atomic and molecular composition of inorganic and organic materials. As an analytical technique it possesses distinct advantages:

1. Increased sensitivity over most other analytical techniques because the analyzer, as a mass-charge filter, reduces background interference.
2. Excellent specificity from characteristic fragmentation patterns to identify unknowns or confirm the presence of suspected compounds.
3. Information about molecular weight.

13.1 INSTRUMENT DESIGN

Functionally, all mass spectrometers have these components (Fig. 13.1): (1) inlet sample system, (2) ion source, (3) ion acceleration system, (4) mass (ion) analyzer, (5) ion-collection system, usually an electron multiplier detector, (6) data-handling system, and (7) vacuum system connected to components (1) through (5). To provide a collision-free path for ions once they are formed, the pressure in the spectrometer must be less than 10^{-6} torr.

13.1.1 Inlet Sample Systems

Gas samples are transferred from a vessel of known volume (3 mL), where the pressure is measured, into a reservoir (3 to 5 L). Volatile liquids are drawn through a sintered disk into the low-pressure reservoir in which they are vaporized instantly. Oftentimes a nonvolatile compound can be converted into a derivative that has sufficient vapor pressure.

The gaseous sample enters the source through a pinhole in a piece of gold foil. For analytical work, molecular flow (where the mean free path of gas molecules is greater than the tube diameter) is usually preferred. However, in isotope-ratio studies viscous flow (where the mean free path is smaller than the tube diameter) is employed to avoid any tendency for various components to flow differently from the others.

13.2 IONIZATION METHODS IN MASS SPECTROMETRY

Ionization methods in mass spectrometry are divided into gas-phase ionization techniques and methods that form ions from the condensed phase inside the ion source. All ion sources are required to produce ions without mass discrimination from the sample and to accelerate them into the mass

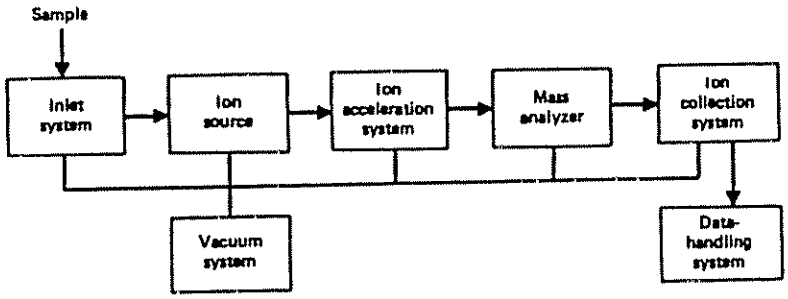

FIGURE 13.1 Components of a mass spectrometer. (*From Shugar and Dean, The Chemist's Ready Reference Handbook*, McGraw-Hill, New York, 1990.)

analyzer. The usual source design has an ion withdrawal and focusing system. The ions formed are removed electrostatically from the chamber. Located behind the ions is the repeller, which has the same charge as the ions to be withdrawn. A strong electrostatic field between the first and second accelerating slits of 400 to 4000 V, which is opposite in charge to the ions, accelerates the ions to their final velocities.

13.2.1 Electron Ionization

The electron ionization source is a commonly used ionization method. The ionizing electrons from the cathode of an electron gun located perpendicular to the incoming gas stream collide with the sample molecules to produce a molecular ion. A source operating at 70 V, the conventional operating potential, also has sufficient energy to cause the characteristic fragmentation of sample molecules.

Some compounds do not produce a molecular ion in an electron ionization source. This is a disadvantage of this source.

A mass spectrometer is calibrated in the electron ionization mode. Perfluoroalkanes are often used as markers because they provide a peak at intervals of masses corresponding to CF_2 groups.

13.2.2 Chemical Ionization[1]

Chemical ionization results from ion–molecule chemical interactions that involve a small amount of sample with an exceedingly large amount of a reagent gas. The source must be tightly enclosed with an inside pressure of 0.5 to 4.0 torr. The pressure outside the source is kept about 4 orders of magnitude less than the inside by a differential pumping system.

Often the primary reason for using this technique is to determine the molecular weight of a compound. For this purpose a low-energy reactant, such as *tert*-$C_4H_9^+$ (from isobutane) is frequently used. In the first step the reagent gas is ionized by electron ionization in the source. Subsequent reactions between the primary ion and additional reagent gas produce a stabilized reagent gas plasma. When a reagent ion encounters a sample molecule (MH), several products may be formed:

MH_2^+ by proton transfer

M^+ by hydride abstraction

MH^+ by charge transfer

Practically all the spectral information will be clustered around the molecular ion, or one mass unit larger or smaller, with little or no fragmentation. This type of ionization is desirable when an analysis of a mixture of compounds is needed and the list of possible components is limited. The general absence of carbon–carbon cleavage reactions for the chemical ionization spectra means that they provide little skeletal information.

Negative chemical ionization[2] can be conducted with hydroxide and halide ions. For these studies the charges on the repeller and accelerating slits in the ion source are reversed with the repeller having a negative charge.

13.2.3 Other Ionization Methods

The less frequently used ionization methods receive only brief mention here. For more details consult the references cited.

[1] B. Munson, "Chemical Ionization Mass Spectrometry," *Anal. Chem.* 49:772A (1977).
[2] R. C. Dougherty, "Negative Chemical Ionization Mass Spectrometry," *Anal. Chem.* 53:625A (1981).

Field ionization[3] and *field desorption*[4] are techniques used for studying surface phenomena such as adsorbed species and trapped samples, and the results of chemical reactions on surfaces; they are also suitable for handling large lipophilic polar molecules.

Fast atom bombardment[5] and *plasma (californium-252) desorption*[6] techniques deal rather effectively with polar substances (usually of higher molecular weight) and salts. Samples may be bulk solids, liquid solutions, thin films, or monolayers.

In *thermal ionization* the sample is put on a filament substrate (a metal ribbon), which is heated in the mass spectrometer source until the sample evaporates (ca. 2000°C). Filament-loading procedures tend to be element-specific. Both positive and negative ions are produced, and thermal ionization usually results in the formation of long-lived, stable ion beams. Thermal ionization is appropriate for inorganic compounds that have ionization potentials in the range from 3 to 6 eV. On the other hand, the technique is inefficient for organic compounds because their ionization potentials usually range from 7 to 16 eV.

Laser desorption methods[7–9] produce a microplasma that consists of neutral fragments together with elementary molecular and fragment ions. Suitable mass spectrometers are limited to time-of-flight and Fourier-transform spectrometers.

The recent development of *electrospray ionization*[10] has extended the range of masses amenable to study by mass spectrometry to above several hundred kilodaltons, and commercial instruments are available.

13.3 MASS ANALYZERS

The function of the mass analyzer is to separate the ions produced in the ion source according to their different mass–charge ratios. The analyzer section is continuously pumped to a very low vacuum so that ions may be passed through it without colliding with the gas molecules. The energies and velocities v of the ions moving into the mass analyzer are determined by the accelerating voltage V from the ion source slits and the charge z on the ions of mass m:

$$\frac{1}{2}m_1v_1^2 = \frac{1}{2}m_2v_2^2 = \frac{1}{2}m_3v_3^2 = \ldots = zV \tag{13.1}$$

13.3.1 Magnetic-Deflection Mass Analyzer

In a single-focusing magnetic-sector mass analyzer, the ion source, the collector slit, and the apex of the sector shape (usually 60°) are colinear. Upon entering the magnetic field, the ions are classified and segregated into beams, each with a different m/z ratio.

$$\frac{m}{z} = \frac{H^2r^2}{2V} \tag{13.2}$$

[3] M. Anbar and W. H. Aberth, "Field Ionization Mass Spectrometry," *Anal. Chem.* 46:59A (1974).
[4] W. D. Reynold, "Field Desorption Mass Spectrometry," *Anal. Chem.* 51:283A (1979).
[5] M. Barber et al., "Fast Atom Bombardment Mass Spectrometry," *Anal. Chem.* 54:645A (1982).
[6] R. D. MacFarlane, "Californium-252 Plasma Desorption Mass Spectrometry," *Anal. Chem.* 55:1247A (1983).
[7] R. J. Conzemius, "Lasers and Mass Spectrometry," *Anal. Chem.* 56:485A (1984).
[8] E. R. Denoyer et al., "Laser Microprobe Mass Spectrometry: Basic Principles and Performance Characteristics," *Anal. Chem.* 54:26A (1982).
[9] D. M. Hercules et al., "Laser Microprobe Mass Spectrometry: Applications to Structural Analysis," *Anal. Chem.* 54:280A (1980).
[10] C. M. Whitehouse et al., *Anal. Chem.* 57:675 (1985).

spectrometer,[15] and inductively coupled plasma–mass spectrometer.[16] Triple quadrupole instruments are now routinely used in protein structure determinations, pesticide residue analysis, and drug metabolism studies.

13.3.7 Resolving Power

The most important parameter of a mass analyzer is its resolving power. Using the *10% valley definition*, two adjacent peaks (whose mass differences are Δm) are said to be separated when the valley between them is 10% or less of the peak height (and the peak heights are approximately equal). For this condition, $\Delta m/m$ equals the peak width at a height that is 5% of the individual peak height.

A resolution of 1 part in 800 adequately distinguishes between m/z values 800 and 801 so long as the peak intensity ratio is not greater than 10 to 1. However, if one wanted to distinguish between the parent peaks of 2,2-naphthylbenzothiophene (260.0922) and 1,2-dimethyl-4-benzoylnaphthalene (260.1201), the required resolving power is

$$\frac{m}{\Delta m} = \frac{260}{260.1201 - 260.0922} = 9319 \tag{13.3}$$

13.4 DETECTORS

After leaving a mass analyzer, the resolved ion beams sequentially strike some type of detector. The electron multiplier, either single or multichannel, is most commonly used.

13.4.1 Electron Multiplier

In the electron multiplier the ion beam strikes a conversion dynode, which converts the ion beam to an electron beam. A discrete dynode multiplier has 15 to 18 individual dynodes arranged in a venetian blind configuration and coated with a material that has high secondary-electron-emission properties. A magnetic field forces the secondary electrons to follow circular paths, causing them to strike successive dynodes.

A microchannel plate is a solid-state electron multiplier composed of a hexagonal close-packed array of millions of independent, continuous, single-channel electron multipliers all fused together in a rigid parallel array. With channel densities on the order of 10^6 per cm^2, these devices are one of the highest pixel density sensors known. Pore diameters range from 10 to 25 μm. The inside of each pore, or channel, is coated with a secondary-electron-emissive material; thus each channel constitutes an independent electron multiplier. The onset of ion feedback within the channel can be staved off by curving each channel in the plate but at the cost of considerable spatial distortion.

13.4.2 Faraday Cup Collector

The Faraday cup collector consists of a cup with suitable suppressor electrodes, to suppress secondary-ion emission, and guard electrodes. It is placed in the focal plane of the mass spectrometer.

[15] R. A. Yost and C. G. Enke, "Triple Quadrupole Mass Spectrometry for Direct Mixture Analysis and Structure Elucidation," *Anal. Chem.* 51:1251A (1979).
[16] R. S. Houk, "Mass Spectrometry of Inductively Coupled Plasma," *Anal. Chem.* 58:97A (1986).